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Soil-site Relationships for Inland Douglas-fir

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Soil-site Relationships for Inland Douglas-fir

ABSTRACT. A soil-site study was conducted for inland Douglas-fir growing in northern Idaho and northwestern Montana. Soil profile descriptions and physical analyses were obtained on 133 plots, along with several physiographic site descriptors. Chemical analyses were performed on soil samples from a third of these plots, and moisture availability was determined on 60 percent of the plots. Site index was based on felled-tree stem analyses. Elevation was the strongest predictor, accounting for a third of the variation in site index. The addition of habitat type information resulted in a significant improvement but still left over half the variation unexplained. After examining numerous soil variables, the standard error could only be reduced 1 foot, a result providing scant reason to go to the time and expense of sampling the soil to predict site index. The causes of these low soil-site correlations could not be conclusively determined, but the most likely explanations are (i) the number of important site factor interactions occurring in this large and complex study area far exceeded the sample size, and/or (ii) failure to measure the true causes of site productivity.

ADDITIONAL KEY WORDS: Pseudotsuga menziesii, site index, soil moisture holding capacity, chemical analysis, habitat type.

¶THE ACCURATE assessment of site productivity is one of the most important aspects of forest land management (Steinbrenner 1979). The most commonly used measure of forest site productivity in North America is site index (Monserud 1984a, Ralston 1964, Spurr 1952), which is defined as the height of the dominant portion of the stand at an index age. The preeminence of site index as a measure of productivity results from the widely acknowledged observation that the height of dominant trees (that have always been dominant) of a given species and age is more closely related to the capacity of a given site to produce wood of that species than any other single measure (Spurr and Barnes 1980).

Obviously the best procedure for measuring site index is to measure the heights and ages of appropriate site trees. Not all sites have suitable site trees, however, for the land may be cut-over, burned-over, or seriously attacked by insect or disease organisms that adversely affect dominant height growth. These situations call for indirect methods of assessing site index, methods that rely on the relationship between environmental factors and site index. Such studies are traditionally called soil-site studies, even though the environmental factors considered often include climatic, physiographic, and vegetative indicators, as well as soil characteristics.

Few soil-site studies of forest land in the Northern Rocky Mountains exist, despite a wealth of information for other areas of the United States and other countries (McGrath and Loewenstein 1975). Of the few studies available for this heavily forested region, most were conducted either by Copeland (1956, 1958) or by Loewenstein and his students (e.g., Wall and Loewenstein 1969, McGrath and Loewenstein 1975, Brown and Loewenstein 1978). After reviewing this small body of literature, McGrath and Loewenstein (1975) listed the following characteristics as the best candidates for giving some indication of site quality: elevation, slope, aspect, soil depth, effective soil depth, water holding capacity, and texture.

In the few reported cases of site quality correlated with soil and physiographic factors in the Northern Rocky Mountains, the studies were conducted over a very limited geographic area, and usually on a single geologic and soil type. In a study on a 4.3 mi² tract in the University of Idaho Experimental Forest, McGrath (1975) found Douglas-fir site index related to elevation, effective rooting depth, wet consistency of the second horizon, and texture of the third horizon. He also found that the site index of western larch was related to depth of the organic horizon, and pH of the fourth horizon, while grand fir site index depended on organic matter, nitrogen, and soil color in the first horizon, and extractable magnesium in the second horizon. Such diverse results for species sharing the same small geographic area suggest that the relationships likely would not be usable outside that study area.

Holmes and Tackle (1962) examined lodgepole pine stands in western Montana and reported 89 percent of the variation in the height of dominants was explained by stand characteristics alone. These included stems per acre, dominant diameter, crown ratio, age, and basal area. A wide variety of soil physical and chemical descriptors and their transformations were also considered, including silt and clay in the B horizon weighted by the effective depth of the B horizon, effective depth to the C horizon, available moisture, organic matter, nitrogen and exchangeable phosphorus and potassium in the B horizon. The addition of soil factors did not improve the height predictions beyond that provided by the stand characteristics alone.

In spite of the great importance of inland Douglas-fir (Pseudotsuga menziesii [Mirb] Franco var. glauca) in the forests of the Rocky Mountains (USDA Forest Service 1973), only recently have site index and height growth curves based on stem analysis data become available (Monserud 1984a, 1985a). These curves are much more accurate than previous curves for this area, which were based on temporary inventory plots and guide curve methods (see discussion by Monserud 1984b, 1985b). One of the objectives of Monserud's site index study was to examine the relationships between environmental variables and site index. The goal was to find edaphic factors that could be used to reliably estimate site index in the absence of site trees. This paper reports the results of that phase of the site index study.

METHODS

Study Area.--The 100-mile by 250-mile study area in northern Idaho and northwestern Montana (Fig. 1) is almost completely mountainous. It is characterized by interlocking networks of accordant ridges and narrow, V-shaped valleys, except for the flat-bottomed glaciated valleys in the northern third of the study area (Ross and Savage 1967). Except for the glaciated trench-faulted northern ranges (oriented northwest-southeast), the mountains that compose most of the study area are sprawling rather than oriented into obvious ranges. Almost all of these mountains are capable of supporting forest vegetation from the valley bottoms to the ridge tops. The ridges rarely exceed 7,000 feet, so no true alpine zone exists in the study area (Cooper, Neiman, and Steele 1983). A variety of igneous, sedimentary, and metamorphic rocks form the mountain masses, but these have no extreme physical or chemical properties that play a conspicuous role in determining the character of the vegetation (Daubenmire and Daubenmire 1968). A major feature of the soil is eolian deposits, especially loess from Columbia Basin silts and volcanic ash (tephra). These windborne materials are deepest on the leeward slopes, which are primarily northeast in aspect. In the glaciated northern ranges, these eolian deposits have been partially replaced by stonier, less productive material in the uplands and coarse alluvium on the scoured-out valley bottoms. In comparison with other parts of the Rockies, the shallowness and stoniness of soils play a relatively minor part in the forest distribution (Daubenmire and Daubenmire 1968). The western fringes of the study area are underlain by Columbia River basalts. These basalts are not generally exposed and do not constitute

the dominant weathering material, for it is here that the eolian mantle is thickest. Soils to the east of this fringe are formed from Precambrian Belt Supergroup metasediments in both the central and glaciated northern portion of the area, and formed from granitics of the Idaho Batholith in the south (Cooper, Neiman and Steele 1983).

The climate of the study area is dominated by the prevailing westerlies, which carry the Pacific maritime regime into northern Idaho and northwestern Montana. The summers are short with scant precipitation and low humidity and the winters are long with heavy snowfall and fairly low temperatures (Haig et al. 1941). A summer drought in July and August is common (Haig et al. 1941). The climate is essentially mediterranean even though the western border of the study area is at least 350 mi inland. This maritime influence is strongest near the Canadian border and decreases to the south. A west-east moisture gradient also exists that results both from orographic lifting and depletion of available moisture as successive mountain ranges are crossed (Cooper, Neiman, and Steele 1983). Although elevation is obviously a strong determinant for moisture availability, the existence of these complex environmental gradients renders a simple descriptor such as elevation an unreliable indicator of precipitation or soil moisture availability (Daubenmire 1968).

Plot Selection Criteria.--Monserud (1984a) located 135 plots throughout the seven National Forests in northern Idaho and northwestern Montana (Fig. 1). Plots were selected to cover a wide range of ages and habitat types, and no requirements were placed on species composition, spacing, stand density, or age structure. Thus, both even- and uneven-aged plots were selected, with both pure and mixed species composition. Site trees selected were the three most vigorous (based on increment cores) dominant Douglas-fir on an approximately 1/2-acre plot that was representative of the stand.

Habitat typing is a land classification scheme that relies on both overstory and understory plant indicators to estimate the expected climax vegetation. The sound ecological basis of forest habitat typing has made it a widely accepted management tool in the Rocky Mountains (Pfister and Arno 1980). Because the factors that determine the habitat type of a site were also expected to affect the shape of the height growth curve, Monserud (1984a) stratified his sample plots so that all five of the major habitat series containing Douglas-fir were well represented. These five habitat series are: (i) the Douglas-fir series (27 plots); (ii) the grand fir (Abies grandis) series (33 plots); (iii) the western redcedar (Thuja plicata) series (33 plots); (iv) the western hemlock (Tsuga heterophylla) series (18 plots); and (v) the subalpine fir (A. lasiocarpa) series (24 plots). These five series will be abbreviated DF, GF, WRC, WH, and SAF, respectively.

Plot Measurements.--Using a stem analysis of three felled site trees per 1/2-acre plot, site index was defined as their average height at an index age of 50 years at breast height (4.5 feet). Based on 135 plots, site index ranged from 28 to 100 feet with a mean of 66 feet and a standard deviation of 14 feet; Monserud (1984a, Table 2) breaks these statistics out by habitat series and age class.

Above-ground field descriptors included the following: slope, aspect, elevation, latitude, longitude, position on slope, shape of slope, and habitat type based on either Daubenmire and Daubenmire (1968), Steele et al. (1976), or Pfister et al. (1977). Average annual precipitation was obtained from isohyetal maps with 10-inch contours (PNW River Basins Commission 1969). Monthly solar radiation estimates for April through September were obtained using S. Childs' SOLRAD program¹, which calculates both direct and indirect radiation based on the methods of Kaufmann and Weatherred (1982). Elevation was measured to the nearest 100 feet using a pocket altimeter. Table 1 shows that a broad and representative range of slopes, aspects, and elevations were sampled within each habitat series.

¹Stuart Childs, Department of Soil Science, Oregon State University, Corvallis.

Below-ground field descriptors were obtained from one soil pit per plot on 133 of the 135 plots. All soil horizons were sampled and described by soil scientists² according to Soil Survey Staff (1975) procedures. Descriptors included taxonomic label, depth of the horizon, color, texture, structure, permeability, and drainage class. Additional descriptors were source of parent material, geologic type of bedrock, observed compaction, and depth (but not purity) of volcanic ash-derived horizons. Table 2 lists sample size for each descriptor measured. Total soil depth was often unknown because the depth of the bottom horizon on a large number of sites (51 plots) exceeded 60 inches. Over half (74) of the plots had volcanic ash-derived horizons, which averaged 16.5 inches when present. A total of 516 separate horizons were identified and sampled on the 133 plots.

²Ula Moody sampled the Kaniksu, Coeur d'Alene, and Lolo National Forests along with parts of the St. Joe and Clearwater National Forests. Dick Cline sampled the Nezperce National Forest. Dale Wilson sampled the Clearwater National Forest. Lou Kuennen sampled the Kootenai National Forest. Norm Yogurst sampled part of the St. Joe National Forest. The authors are grateful for the invaluable contribution of these individuals.

Below-ground laboratory descriptors on a subset of the plots were obtained from analyses by the Soil Characterization Laboratory at the University of Idaho. Due to the expense of laboratory analysis, not all 516 horizon samples were analyzed for all laboratory descriptors. Soil samples were oven dried at 39°C, ground, and screened to pass a 2-mm sieve. The modified pipette method (Kilmer and Alexander 1949, Jackson 1956) was used for particle size analysis. Moisture retention at -1/3 bar and -15 bar (Salinity Laboratory Staff 1954) was determined for 266 horizons from 76 plots (Table 2). Volumetric moisture-holding capacity was calculated from the difference between -1/3 and -15 bar moisture content and bulk density.

Saturated soil paste samples were used to determine pH (Salinity Laboratory Staff 1954). Exchangeable cations, calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K) were extracted from samples from 58 of the plots using 1N ammonium acetate buffered to pH 7 (Soil Conservation Service 1972). Calcium and magnesium were determined with a Perkin-Elmer Model 360 Atomic Absorption Spectrophotometer. Sodium and potassium were determined with an Eppendorf Flame Photometer. Cation exchange capacity (CEC) was determined on samples after leaching with 1N ammonium acetate using a modified Soil Conservation Service procedure (1972).

Kjeldahl nitrogen (N) was determined by digestion with concentrated H_2SO_4 , with K_2SO_4 salt and Hg catalyst in a Technicon Model BD-20 block digester. Ammonium resulting from the digestion was determined on a Technicon Autoanalyzer II using the automated phenate method.

Organic carbon was determined by the modified Walkley-Black method (Walkley 1935) using 1N $\text{K}_2\text{Cr}_2\text{O}_7$ and concentrated H_2SO_4 heated to 150°C , cooled, and filtrated using 0.5N FeSO_4 . Organic matter (OM) was then estimated by multiplying the calculated organic carbon by 1.72.

Available phosphorus was determined on samples from 28 of the plots using the sodium acetate method of Greweling and Peech (1965). Samples were shaken with activated carbon and sodium acetate solution, and phosphorus in the filtrate was determined by the stannous chloride-molybdenum blue procedure using a Perkin-Elmer Model 54 spectrophotometer.

ANALYSIS

Linear regression was used to predict site index as a function of the various edaphic factors using the GLM and REG procedures of the SAS Institute (1982). The STEPWISE procedure was used occasionally for some screening purposes, but this application was minor. A 5 percent level of significance was required in all model development. Dummy variables (Draper and Smith 1981) were used for all categorical data (e.g., habitat type). All R^2 statistics reported are adjusted for degrees of freedom (Draper and Smith 1981).

Transformations.--To reduce the number of variables under consideration in the analysis, several categorical variables were transformed to a continuous scale (Table 3) by assigning the midpoint of the range of possible values for the respective category or class. The hue component of color was transformed to a continuous scale, while the value and chroma components were already continuous. Permeability rate class was converted to a single rate (inches/hour), and the texture class was transformed to both percentage clay and percentage silt plus clay. Several variables could not be transformed to a continuous scale (Table 4): parent material, bedrock, drainage class, structure, compaction, slope position, and slope shape.

All laboratory variables were expressed on a volumetric basis (i.e., mass per soil volume) by multiplying by the rock-free proportion and bulk density. The thickness of each horizon was used in calculating a weighted average when combining horizon variables. Categorical variables such as structure were also "averaged": the thickest (i.e., modal) category was used to represent the plot (or horizon).

Three sets of horizon and soil depth variables were calculated from all of the data available for each horizon. First, all master horizons (A, B, or C) were combined by using the thickness of the respective horizon as a weight. Because the first horizon on several plots was a B rather than an A, a second set of horizon variables was created based on their position in the profile from the top down: horizons were labeled 1, 2, and 3, rather than A, B, and C. The third set of variables ignored the A-B-C master horizons completely and instead used the following four soil depth classes: 0-6 in, 6-12 in, 12-24 in, and greater than 24 in.

Several soil depth variables were calculated, including thickness of the A, B, and C horizons and total soil depth. Effective soil depth was also calculated by using only the rock-free proportion of the soil. As previously mentioned, several plots had soils that were quite deep (>60 in), and thus, depth could not be accurately determined. In those cases, the estimated thickness of the last horizon was taken to be the overall average thickness of that horizon (B or C) on plots where its thickness was known. The average thicknesses of the B and C horizons were 22.5 inches and 33 inches, respectively. Assuming that a horizon with a high bulk density or a high rock percentage could possibly limit downward root penetration (Copeland 1958), several limiting depth variables were calculated: depth to horizons with bulk densities greater than or equal to 1.6 and 1.7 g·cm⁻³, and depth to horizons with rock percentages exceeding 30, 40, 50, . . . , 90.

The last category of variables considered was moisture-holding capacity, which was defined to be the amount of water held between -1/3 and -15 bars (Hausenbuiller 1972). Moisture-holding capacity was calculated on a volumetric basis for each profile. To try to capture the effect of downward slope water movement, an additional moisture variable was created by multiplying moisture-holding capacity by slope percentage. Soil moisture to a limiting depth was calculated by using the same soil depth limiters (high bulk density or rock percentages) previously mentioned to estimate the total moisture available to roots on each plot. A logarithmic transformation of each of these variables was also examined because a given difference below the mean was expected to be more important to growth than the same difference above the mean.

In summary, all below-ground descriptors were analyzed by classifying the soil profile five different ways: (i) by A, B, and C horizons, (ii) by position of the horizon in the profile (i.e., uppermost, second, third), (iii) by four soil depth classes, (iv) by plot average weighted by horizon thickness, and (v) by plot average above a potentially limiting depth.

RESULTS

The soil-site models discussed here used environmental factors other than tree height and age to predict site index. Models using tree height and age have already been developed for this data (Monserud 1984a, 1985a); their standard error (SE) is 4 feet. Because site index in this sample of 135 plots had a standard deviation of 14 feet, a useful soil-site model obviously must predict site index with a standard error substantially less than 14 feet. And because it is unlikely that environmental factors alone could lower the standard error below the 4-foot level attained by using height and age, the standard error of any soil-site model developed from this data will likely be between 4 feet and 14 feet.

Above-ground Descriptors.--The environmental factor most strongly related to site index in this study was elevation; standard error was 11.7 feet and R^2 was 31 percent. A quadratic elevation term was insignificant.

Habitat type was also significantly related to site index, but not as strongly as elevation. Because of insufficient sample size for some habitat types, the data were combined by habitat series. The resulting 5 habitat series explained a significant amount of variation ($SE = 12.6$ feet and $R^2 = 21$ percent). Using elevation in combination with habitat series further reduced the standard error to 11.2 feet ($R^2 = 35$ percent). A full analysis of covariance was then performed to identify the specific interactions between elevation and habitat series. Results indicated that 1) there was a common intercept for all habitat series and that 2) the slope in the elevation term was significantly different for two groups of habitat series. Site index decreased more rapidly with increasing elevation if habitat series was either DF, WH, or SAF rather than GF or WRC. The specific model is:

$$\hat{SI} = 94.29 - (0.605 \cdot Z_{23} + 0.790 \cdot Z_{145}) \cdot ELEV \quad [1]$$

where:

SI is site index (total height at index age of 50 years at breast height)

ELEV is elevation in 100's of feet, and the dummy variables are:

$Z_{23} = \begin{cases} 1 & \text{if habitat type is in the GF or WRC series, or} \\ 0 & \text{otherwise.} \end{cases}$

$Z_{145} = \begin{cases} 1 & \text{if habitat type is in the DF, WH, or SAF series, or} \\ 0 & \text{otherwise.} \end{cases}$

This model explained 39 percent of the variation and had a standard error of 11.1 feet. The two different decreasing trends in site index with respect to increasing elevation are illustrated in figures 2a and 2b. Although this model is only concerned with the level of site index, Monserud (1984a) found that the shape of the site index curves also differed between similar habitat series groupings.

No other above-ground descriptors were important. Neither latitude nor annual precipitation explained more than 3 percent of the variation in site index. Slope and aspect likewise were unrelated to site index, even when used in Stage's (1976) slope-aspect transformation. Both monthly and total solar radiation during the growing season were also insignificant, as was the ratio of radiation to precipitation. Although slope position and slope shape were significant when used separately (SE = 13.1 feet), they were insignificant when used in addition to elevation and habitat series.

Below-ground Field Descriptors.--Several below-ground field descriptors were significant: parent material, bedrock, drainage class, soil depth, and the thickness of the C horizon. These five descriptors (13 variables) had a standard error of 12.9 feet with $R^2 = 16$ percent. The addition of elevation and habitat series lowered the standard error to 10.3 feet.

In addition to C-horizon thickness and total soil depth, two other soil depth variables were significant: the depth to a horizon with a bulk density of $1.7 \text{ g}\cdot\text{cm}^{-3}$ or more, and the depth to a horizon with at least 90 percent rock. Both limiting depth variables were insignificant, however, when used in conjunction with elevation and habitat series.

Analyzing the soils data by horizon presented a problem with sample size. When simultaneously looking at variables from all horizons, only the 53 plots with A, B, and C horizons present were considered. All other plots contained missing values, which meant that only 40 percent of the plots could be examined in such an analysis. Using the reduced set of 53 plots, stepwise regression found six variables significant in addition to elevation: thickness of the A and B horizons, and the chroma component of color (which measures brightness) for the A, B, and C horizons as well as average chroma for the plot. This model had a standard error of 9.2 feet; elevation alone had a standard error of 12.2 feet on this subset. Suspecting that this model might be overfitting the data, the analysis was redone using the larger subset of 84 plots with both A and B horizons present. The suspicion was confirmed, for only one of the horizon variables was significant: chroma of the B horizon. When combined with elevation, a standard error of 11.2 was produced, compared to a standard error of 11.6 using only elevation. Furthermore, no horizon variables were significant in combination with elevation and habitat series (SE = 10.9 feet).

Horizon variables were also analyzed based on the position of the horizon in the soil profile. For example, data from all the uppermost horizons were grouped even though some were from A horizons and others were from B horizons. When stepwise regression was used with the larger subset of 114 plots that contained two different master horizons (e.g., A and B, or B and C), the thickness of the uppermost horizon was the only significant horizon variable; standard error was 11.5 feet when used with elevation, whereas standard error was 11.6 feet with elevation alone.

Each horizon was also examined separately. For the 85 plots with an A horizon, only rock percentage of the A horizon was significant with elevation (SE = 11.5 feet). Rock percentage was likewise the only B-horizon variable significant (with elevation) on the 127 plots containing a B horizon (SE = 11.0 feet). And for the 82 plots with a C horizon, hue and clay percentage of the C horizon were the only variables significantly related to site index (SE = 12.0 feet). As with all other analyses reported here, elevation was the most significant predictor of site index for all of these subsets of the data.

The failure of the soil horizon variables to explain a substantial amount of variation in site index prompted consideration of soil depth classes rather than horizons. This strategem was not successful however, for the best model (elevation, clay percentage, and rock percentage of the 0 to 6-inch class, and chroma of the 6 to 12-inch class) produced a standard error of only 10.9 feet; adding habitat series further reduced the standard error only slightly, to 10.8 feet.

Below-ground Laboratory Descriptors.--Of the 58 plots with laboratory data, 30 had A horizons, 52 had B horizons, and 24 had C horizons. Because only 15 of these plots had profiles with A, B, and C horizons, the simultaneous analysis of all horizon data simply was not meaningful. Analyzed separately by horizon, the only significant factors were K for the A horizon (SE = 13.1 feet), K for the B horizon (SE = 13.5 feet), and Mg for the C horizon (SE = 14.3 feet). Based on a weighted average (by thickness) of horizon data, the only significant plot factors were K and organic matter (SE = 13.4 feet). Adding elevation to the analysis changed these results: no laboratory descriptors from the A horizon were significant (SE = 11.6 feet), and pH rather than K was significant for both the B horizon (SE = 11.6 feet) and the overall plot average (SE = 12.1 feet). For the C horizon, Mg was still the only significant laboratory descriptor.

Analyzing the horizon data by position in the profile rather than by A, B, and C horizons produced similar results. The only significant factor in the uppermost horizon was K, both with (SE = 11.5 feet) and without elevation. Both Mg and Ca of the second horizon were significant, although only Ca remained significant with elevation (SE = 11.8 feet). No factors in the third horizon were significant.

The third analysis of the laboratory data used four soil depth classes rather than horizons. When elevation was excluded, the most significant factor for each of the depth classes was K, whether the classes were analyzed separately or jointly; all standard errors exceeded 12.8 feet, however, indicating a weak effect. When elevation was added and the depth classes were analyzed separately, K was no longer significant (except for the deepest soil class) and was replaced by pH; standard errors ranged from 10.3 feet to 11.6 feet.

Simultaneously analyzing elevation and laboratory descriptors from all four soil depth classes produced an interesting result: elevation and 10 laboratory descriptors were significant, producing a standard error of 6.8 feet, with $R^2 = 75$ percent. The significant factors were: pH, Na, and K for the 0 to 6-inch class; Na and percentage organic matter in the 6 to 12-inch class; N in the 12 to 24-inch class; and pH, Mg, K, and N in the >24-inch class. This result is based on only 44 plots, however, so the possibility of overfitting this limited sample with such a large number of predictors is great. Mallows' (1973) Cp statistic was very close to the number of parameters (12), indicating the model is probably not biased by lack of fit (Draper and Smith 1981).

Examination of the residuals revealed that one of the observations was quite influential. Deleting this observation resulted in four variables (K and Na for the 0 to 6-inch class, Na for the 6 to 12-inch class, and Mg for the >24-inch class) being replaced by three other variables (organic matter in the 0 to 6-inch class, pH of the 12 to 24-inch class, and Ca for the >24-inch class) by the stepwise selection procedure. This new model explained essentially the same amount of variation. The new and old models predicted the deleted observation with an error of 54 feet and 2 feet, respectively, indicating its extreme importance. This is cause for concern that these models may extrapolate poorly to the remainder of the population. McQuilkin's (1976) admonitions regarding the ease of overfitting soil-site data are quite relevant here.

Although not an independent test, these chemical models were also fit using a different dependent variable: site index based on index age 100 rather than 50 years. Results were similar to those using an index age of 50 years. When the model with elevation and 10 significant laboratory descriptors was used, all variables except Na in the 0 to 6-inch class were significant ($R^2 = 61$ percent). Standard error was 10.6 feet compared with 14.5 feet using only elevation and 18.3 feet using only the mean site index. Examination of residuals did not reveal a problem with influential observations.

Expecting that moisture-holding capacity would be the most important laboratory variable, sample size was increased to 266 horizons, which represented 76 plots. This expectation was not realized, however, for none of these moisture variables explained more than a trivial amount of variation in site index. Although several variables were significant (e.g., total moisture, moisture above a horizon either with bulk density exceeding $1.7 \text{ g}\cdot\text{cm}^{-3}$ or percentage rocks exceeding 90, moisture in the uppermost and in the second horizons, and moisture below 24 inches), the greatest reduction in standard error over using elevation alone was only 0.3 feet. The logarithmic transformation was only slightly better. No combination of moisture variables produced a standard error below 13 feet in the absence of elevation.

DISCUSSION

The surprising aspect of this study is not that elevation and habitat type were the strongest predictors of site index, but rather that the myriad of soil descriptors accounted for so little variation. No combination of soil variables accounted for anywhere near the same amount of variation in site index as did elevation and habitat type. Recall that elevation and habitat type are strongly related to several of the major soil-forming factors (climate, living organisms, and topography). Elevation, which is clearly related to both temperature and precipitation, as well as other climatic factors, was the only strong predictor, accounting for approximately a third of the variation in site index ($SE = 11.7$ feet). The addition of habitat type information resulted in a significant improvement, but still left over half of the variation unexplained ($SE = 11.1$ feet; see model [1]). With numerous soil variables to choose from, the standard error could be lowered only another foot. In an ongoing study of genetic variability, Rehfeldt (1979, 1982, 1983) has also found that elevation is the primary environmental factor accounting for variability in both height growth and cold hardiness in young Douglas-fir.

Only one group of variables resulted in a large improvement over elevation: the 10 chemical descriptors that lowered standard error to 6.8 feet. This result is suspect, however, for it is based on only a third of the data (44 plots) and because it requires a large number of

parameters (12, leaving 32 degrees of freedom). The possibility of overfitting this small subset of the data appears great (see also McQuilkin 1976).

The failure of moisture-holding capacity to explain a substantial amount of variation may seem surprising, but there is clear precedence for such a result (e.g., Daubenmire 1968, Broadfoot 1969). Obviously, moisture is critical to tree growth (Kozlowski 1968), but finding a moisture descriptor that is important to the tree is not a trivial matter (Broadfoot 1969). Moisture-holding capacity traditionally has been defined as the difference between field capacity and the wilting point (Hausenbuiller 1972). This definition has several advantages: it is objective, it is a fixed attribute of the soil, and it is ecologically relevant if drought occurs (i.e., the wilting point is reached) after field capacity has been reached. Moisture-holding capacity will obviously fail to be strongly related to productivity if either of these conditions is not met, however. This is the basis of Broadfoot's (1969) criticism of the usual laboratory measure of available moisture: it does not necessarily reflect the moisture actually available during the growing season. For example, low moisture-holding capacity can be offset by timely precipitation during the growing season. Variation among the field capacities of the various soils sampled may contribute somewhat to the poor correlation between moisture-holding capacity and site index. Although the moisture held at $-1/3$ bar is the common definition of field capacity, water available to trees may be held at tensions that range from 0.1 bar for coarse material to 0.5 bar for fine-textured soils (Hausenbuiller 1972).

Daubenmire has probably made the strongest case for expecting available moisture to be poorly related to growth in the Northern Rockies. After observing that soil drought usually occurs only in the top few centimeters of the profile in all habitat series moister than the Douglas-fir series (namely the GF, WRC, WH, and SAF series in this study), Daubenmire (1968) concluded that soil drought appears to be of minor ecological importance. Only in the Douglas-fir and ponderosa pine series do soils dry to the wilting point to a considerable depth each summer (Daubenmire and Daubenmire 1968). Daubenmire (1968) thus concluded that the climax vegetation types more closely reflected the soil moisture regime than did the commonly used abiotic site descriptors. Haig et al. (1941) pointed out that the growth of mature trees in the western white pine type does not strongly rely on growing season precipitation because the subsoils usually remain moist owing to heavy winter snow cover in this study area. The phenology of growth is an additional consideration. In Douglas-fir, one mechanism of adaptation to drought involves completing height growth before the drought normally occurs (G. E. Rehfeldt, personal communication, 1985).

The ecological complexity of the study area is also a likely factor contributing to the poor soil-site correlations. Although this area has historically been regarded as ecologically distinct (e.g., the western white pine type of Haig 1932) because of a mediterranean climate that favors Thuja, Tsuga, Abies, and Pinus monticola, it nevertheless contains considerable diversity. For example, Daubenmire and Daubenmire (1968) recognized eight habitat types that contain Douglas-fir, and Cooper et al. (1983) have expanded (and redefined) this list to include

34 such habitat types. The physiographic complexity of the study area is evident from Table 1. The complexity of the soils and geology in this mountainous area certainly rivals that of the vegetation (Ross and Savage 1967). Compounding this complexity is the interaction between soils and vegetation, which caused Daubenmire much consternation. After finding the same habitat type on several soil series and then finding several habitat types on the same soil type, Daubenmire (1952) rejected a pedological description of the soils as an integral component of his ecologically-based land classification system. This case was later stated more strongly: "No useful correlation exists between vegetation types as defined herein and profile types distinguished on the basis of color, texture, structure, depth, sequence of horizons, etc." (Daubenmire and Daubenmire 1968, p. 52).

Faced with such ecological complexity, the sheer size (25,000 mi²) of the study area increases the difficulty of finding a single set of soil-site factors that are strongly related to growth. Within any area there are surely several site factors controlling growth (e.g., moisture, nutrient, and temperature regimes), and all of these factors are critically interdependent (McQuilkin 1976). If any one of them does not function within an optimum range, the effectiveness of all the others is reduced (Hausenbuiller 1972). Thus, the studies identifying high soil-site correlations are often those that isolate one or two limiting and widely varying environmental factors while holding all others constant (Jones 1969). This is far easier when the study area is small and relatively homogeneous.

An alternate strategy for gaining insight into the workings of a multifactor system when controlled experiments are impossible is to increase sample size drastically. Judging from the soil-site literature, this study's sample size of 133 plots would easily qualify as large, considering that stem analyses were done on every plot. And Broadfoot's (1969) sample size of 739 plots covering six states is clearly enormous. Yet sample size in both studies appears to be small relative to the number of important factor interactions that are likely varying. Broadfoot (1969) regarded the sheer size of his study area as one of the reasons leading to an unsuccessful study. He found significant soil-site relations on small portions of his study area, but they did not generalize to his entire study area. Too many factors were interacting and varying.

Generally speaking, two explanations remain for the lack of a strong soil-site correlation in this study. Either the measured edaphic factors are not directly related to tree growth, or site index is a poor measure of site productivity. The first possibility has already been discussed to a degree regarding the lack of a correlation between site index and the many moisture variables considered. Both Broadfoot (1969) and McQuilkin (1976) concluded that the failure of their studies resulted primarily from the inability to measure the true causes of site productivity, namely moisture and nutrient availability during the growing season, soil aeration, and physical condition including root growing space. Broadfoot (1969, p. 361) goes on to state a conclusion that could just as well have been made about this study: "Apparently, pH, acid-fluoride extractable P, exchangeable K and Na, depth of

topsoil, and clay content do not indicate how much of each nutrient is available to the tree. Neither do available water capacity, inherent moisture condition, presence of a pan, and texture show how much moisture is available during the growing season." This is not to say that soils are unimportant to tree growth, but rather that the commonly measured soil characteristics may not be strongly related to the true causes of productivity.

Another possibility for explaining the lack of correlation between site index and edaphic factors is site index itself. This is unlikely, however, because stem analyses were used to observe the actual height of the site trees at index age. Site index was neither inferred as with guide curve methods (see Monserud 1984b, 1985b) nor predicted, the two problems with site index that Spurr (1955) cautioned against in soil-site studies.

To eliminate the index age of 50 years as a possible cause of the lack of correlation in the current study, the entire analysis was rerun using an index age of 100 years. Results were quite similar. Again, elevation was the only strong predictor, followed by habitat type. No combination of the other soil-site variables was found that explained an important amount of additional variation. These results demonstrate that 50 years is probably an adequate time for integrating site productivity into a reliable height growth index. Similar results from a 100-year base make it unlikely that temporal variation (e.g., changing climate) was the cause for the poor soil-site correlations.

CONCLUSIONS

It is tempting to end by quoting Bob Marshall (1928): "And now for the conclusion--but there isn't any." Such is not the case, however, for the major conclusion--and most surprising aspect--of this study is that the large number of measured soil and physiographic factors explained only a trivial amount of the variability in Douglas-fir site index. Only elevation and habitat type were important, and both are easily measured above-ground descriptors. The low correlations between site index and soil factors does have practical significance, however, for they make it difficult to justify the expense of describing and analyzing soil for such a slight improvement in site index prediction. The two most likely explanations for these low correlations are (i) a large and complex study area where the number of important site factor interactions far exceeded the sample size, and/or (ii) failure to measure the true causes of site productivity.

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TABLE 1. Number of Douglas-fir site index plots by forest habitat series for various levels of aspect, elevation, and slope (after Monserud 1984a).

	Habitat Series					
	Douglas- fir (DF)	Grand fir (GF)	Western redcedar (WRC)	Western hemlock (WH)	Subalpine fir (SAF)	Total
Aspect (degrees)						
1-90	2	5	3	4	1	15
91-180	10	10	9	4	14	47
181-270	11	14	17	4	6	52
271-360	4	4	4	6	3	21
Elevation (feet)						
2000-2900	6	3	7	1	0	17
3000-3900	11	13	18	9	1	52
4000-4900	6	10	7	8	7	38
5000-5900	4	7	1	0	10	22
6000-7000	0	0	0	0	6	6
Series means	3730	4140	3610	3760	5300	4080
Slope (degrees)						
00-10	2	2	4	2	3	13
11-20	4	10	9	2	6	31
21-30	10	8	8	3	11	40
31-40	11	13	12	11	4	51
Series means	27	25	25	28	23	25
Series totals	27	33	33	18	24	135

TABLE 2. Sample size by plot (np) and by horizon (nh)
for all below-ground field and laboratory descriptors.

<u>Field descriptors</u>	<u>np</u>	<u>nh</u>
Taxonomic label	133	516
Horizon depth	82	465
Color	133	505
Texture	133	511
Structure	133	516
Permeability	90	339
Bulk density	133	510
Rock percentage	133	507
Drainage class	133	---
Parent material	133	---
Bedrock type	133	---
Ash depth	133	---
Compaction	38	---
<u>Laboratory descriptors</u>	<u>np</u>	<u>nh</u>
-1/3 bar %M	76	266
-15 bar %M	76	266
Ca	58	191
Mg	58	192
Na	58	189
K	58	192
pH	58	192
CEC	58	192
OM	57	181
N	58	184
P	28	95

TABLE 3. Continuous transformations of several categorical variables.
Sample size (nh) by horizon is given, out of a total of 516 sample horizons.

Color (hue)			Permeability		
Category	Wavelength	nh	Category	Rate ^a	nh
	(nm)			(in/hr)	
5.0 Y	580	3	Very slow	0.05	1
2.5 Y	590	44	Slow	0.13	27
10.0 YR	600	355	Mod slow	0.50	31
7.5 YR	610	93	Moderate	1.65	79
5.0 YR	620	10	Mod rapid	3.75	74
			Rapid	7.50	125
			Very rapid	10.00	1

Texture			
Category	Clay ^b	Silt + Clay ^c	nh
	(%)	(%)	
Sand	5	10	28
Silt	6	90	1
Loamy sand	8	20	74
Sandy loam	10	35	131
Silt loam	14	75	161
Loam	17	60	85
Sandy clay loam	28	45	11
Clay loam	34	70	10
Silty clay loam	34	90	9
Sandy clay	45	50	0
Silty clay	50	95	0
Clay	70	70	1

^aBased on the midpoint of the permeability range (Soil Survey Staff 1975).

^bBased on the midpoint of the percent clay range (Soil Survey Staff 1975).

^cFrom Steinbrenner (1979).

TABLE 4. Categorical variables and sample size. Note that sample size for Structure and Compaction is number of horizons (nh) rather than number of plots (np).

<u>Parent material</u>		<u>Bedrock</u>		<u>Drainage</u>		<u>Structure</u>	
<u>Category</u>	<u>np</u>	<u>Category</u>	<u>np</u>	<u>Category</u>	<u>np</u>	<u>Category</u>	<u>nh</u>
Colluvium	93	Metamorphic	89	Ex well	19	Single grain	40
Residium	7	Igneous	32	Well	92	Weak	157
Till	18	Basalt	6	Mod well	22	Moderate	168
Rocks	6	Mixed	6	Poor	2	Strong	36
Coll/resid	7					Massive	109
Coll/rocks	2						

<u>Compaction</u>		<u>Slope position</u>		<u>Slope shape</u>	
<u>Category</u>	<u>nh</u>	<u>Category</u>	<u>np</u>	<u>Category</u>	<u>np</u>
None	71	Bottom-lower 1/3	17	Concave	14
Low	32	Middle 1/3	46	Straight	38
Low-mod	6	Upper 1/3-top	44	Convex	61
Moderate	36			Irregular	19
Mod-high	4				
High	6				

FIGURE CAPTIONS

FIGURE 1. Douglas-fir site index plot locations.

FIGURE 2a. Site index versus elevation for the GF and WRC habitat series (coded 2 and 3, respectively). The regression line is
 $SI = 94.29 - 0.605 \cdot ELEV.$

FIGURE 2b. Site index versus elevation for the DF, WH, and SAF habitat series (coded 1, 4, and 5, respectively). The regression line is
 $\hat{SI} = 94.29 - 0.790 \cdot ELEV.$

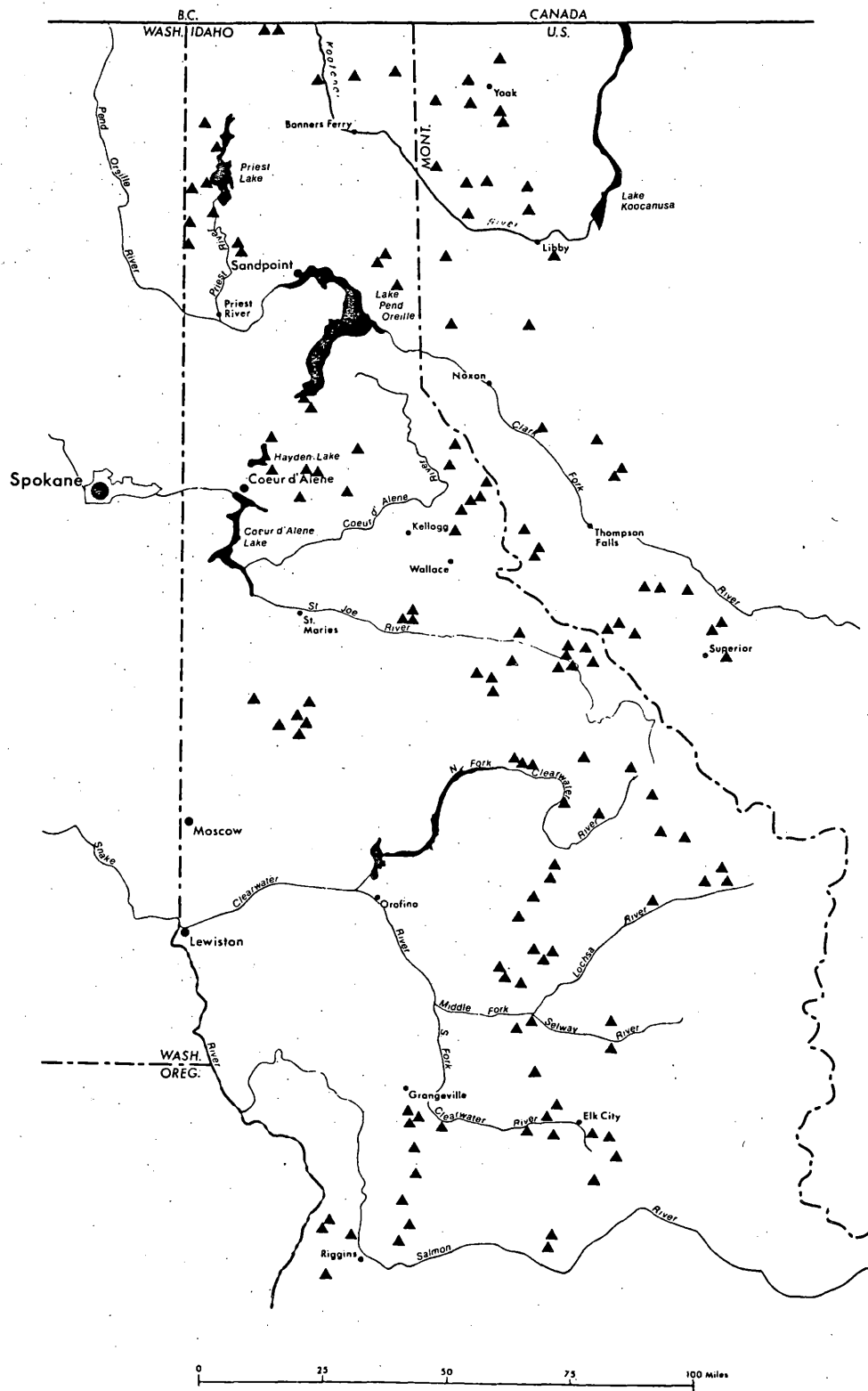
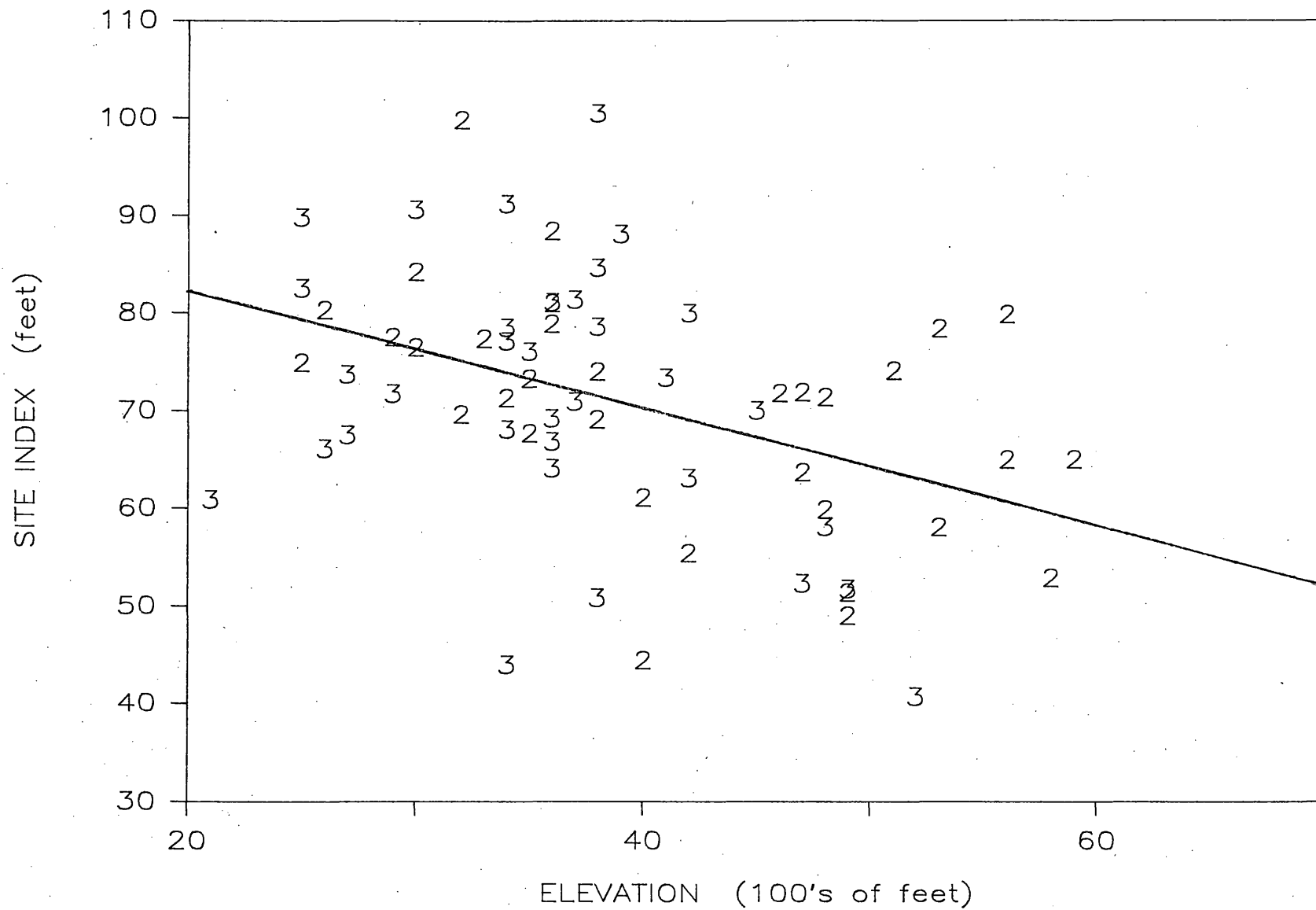


Figure 1.--Douglas-fir site index study plot locations.



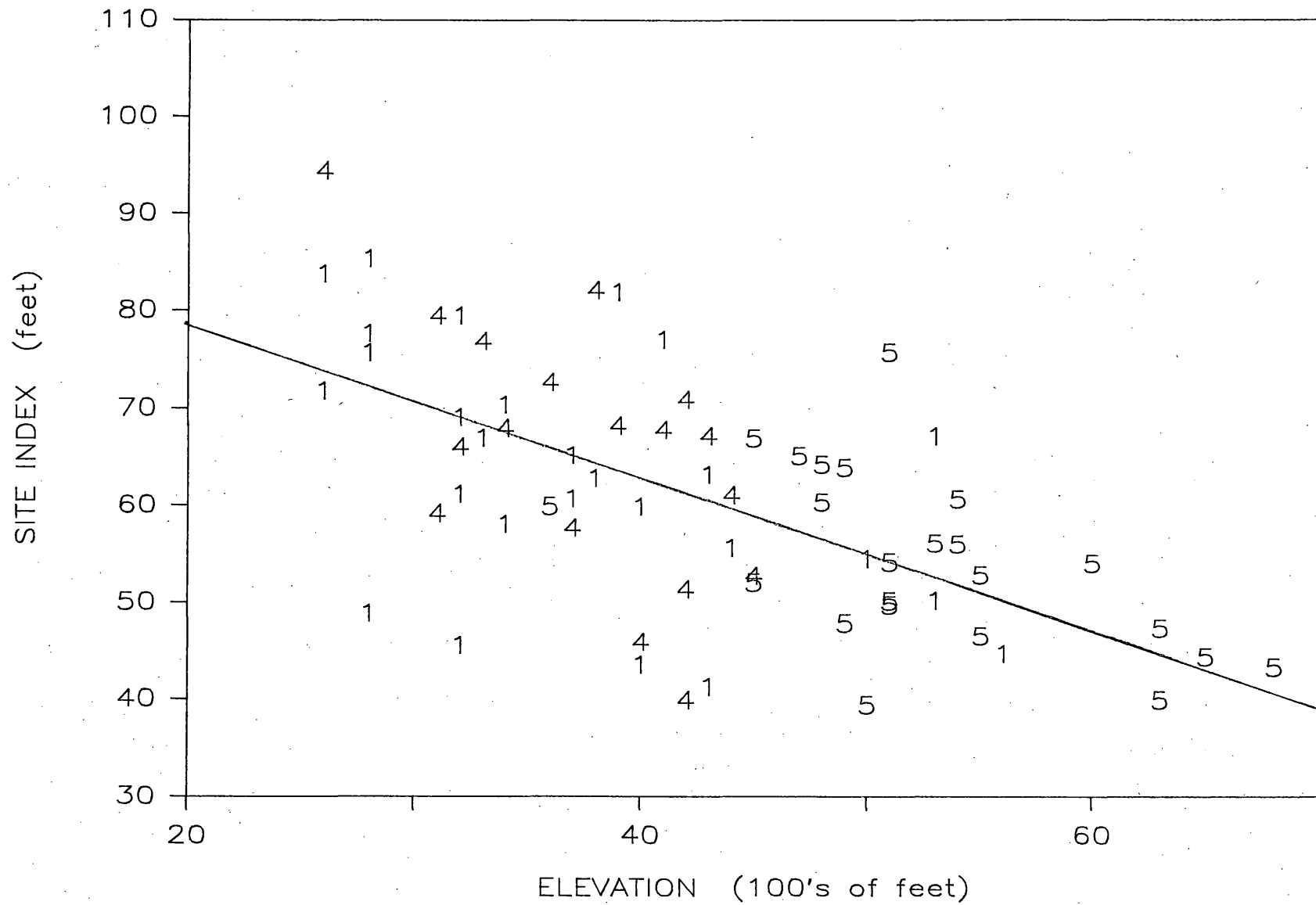


FIGURE 2b